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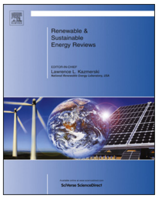

Overview of electric power potential of surplus agricultural biomass from economic, social, environmental and technical perspective—A case study of Punjab

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ABSTRACT

Biomass is a renewable, economic and readily available resource of energy that has potential to substitute fossil fuels in many applications such as heat, electricity and biofuels. The increased use of the agricultural biomass can help the agricultural based societies in achieving energy security and creating employment without causing environmental degradation. But, the viability and feasibility of electricity generation from agricultural biomass depends upon the availability of biomass supply at a competitive cost. The present study investigates the availability of agricultural biomass for distributed power generation in Punjab. The total production of the crop residues has been estimated by residue-to-product ratio (RPR) method. Further, the restrictions introduced by competitive uses as well as harvesting practices are taken into considerations to evaluate the available biomass potential. The biomass power potential has been obtained on considerations of energy contents of the particular crop residues and selecting appropriate conversion route. A total of 55.396 Mt of the agricultural residues are produced from various major crops. Out of these, 22.315 Mt (40.17%) of the agricultural biomass has been found to be surplus with an average density of 443 t/km^2. These surplus residues can significantly be used to provide continuous, reliable and sustainable fuel supply for power plants. Cereals (rice, wheat, maize and barley) have major contribution (74.67%) in the surplus biomass, followed by cotton (25.01%) and sugarcane (0.2%). The estimated annual bio-energy potential of unused crop residues is 0.35 EJ (8.43% of India's potential), which is equivalent to 1.43% India's annual primary energy consumption. It has been revealed that a power potential of 2000–3000 MW can be exploited from these resources depending upon thermal efficiency. The study concludes with a discussion on significance and challenges of decentralized electricity generation for rural energy supply, including brief description about economical, social, environmental and technical aspects of bioelectricity.

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1. Introduction

1.1. Role of renewable energy in energy portfolio

The electricity demand in the world, particularly in India is expected to increase drastically, due to rapid industrial growth and increasing population. The installed capacity of the power plants (Utilities) has increased to about 186 GW (by December, 2011) from a meagre 1.713 GW in 1950 [1]. Similarly, the electricity generation has increased from about 5.1 billion kW h in 1950–1951 to 789 billion kW h in 2010–2011. The per capita consumption of electricity in the country is also increased from 15 kW h in 1950 to about 814 kW h in 2011. Therefore, the country continues to have mismatch between demand and supply and experienced energy and peak shortages to the tune of 8.5% and 10.3% respectively during the year 2010–2011.

The native energy reserves of India are not adequate to fulfill the growing energy requirements in the country. This would result excessive pressure on fossil fuel resources, which have inherent problems such as diminishing fuel reserves, precarious oil markets and global warming. According to Kumar and Jain [2], the consumption of coal, which is the major fuel used to produce electricity in India (with contribution of 53%), has increased from 71.2 million tons (Mt) to 462.7 million tons (Mt) during the period 1970–1971 to 2006–2007. Moreover, the electricity produced by conventional resources (thermal, gas and hydel) is distributed around the country through a centralized grid without reaching the remote areas. Non-access to electricity and rural poverty are closely correlated.

Electricity is a prerequisite for improving living standard, also an essential input for productive and economic activities [3]. Poor electricity supply not only hampers household activities but also badly affect health facilities, education system and agricultural activities in rural areas [4]. The growth of rural industries including agro based industries is also badly affected due to inadequate supply of assured electricity in rural areas. This in turn results in unemployment and associated socio-political problems in a region.

To ensure continuous power supplies to these areas, there is urgent need to construct decentralized power plants, based on renewable energy resources available in a region [4–5]. It has been revealed that only 18% of global electricity is currently met by renewable sources and without hydropower it is only 2.5% [6]. Although the renewable energy sources accounts for 33% of India's primary energy consumption, but their share in the total installed capacity (excluding large hydropower projects) was only 12.7% in June 2014 [7].

India is increasingly adopting responsible renewable energy techniques and taking positive steps towards carbon emissions, cleaning the air and ensuring a more sustainable future [8]. The Government of India (GoI) has also made it mandatory for State Electricity Boards (SEBs) with favourable policy incentives to supplement installed capacity through renewable energy resources.

Solar, wind, micro-hydro and biomass are some of the feasible components of renewable energy resources, which can be used to produce heat, electricity and mechanical energy. Each of these options has its own merits and demerits, primarily due to location specific availability of the resources. In an report presented by statistical office (GoI), it was revealed that the wind energy can be used to produce about 50 GW of electric power, while the hydro and biomass resources (including cogeneration bagasse) has power potential of 15 GW and 22 GW, respectively [9]. The source-wise estimated potential of renewable energy sources is presented in Fig. 1. Therefore, these resources can be explored for sustainable development and energy security in various parts of the country.

1.2. Status of bio-energy and future planning

1.2.1. Sustainability and current uses of biomass resources

In the past decade, there has been renewed interest in the biomass as a renewable energy source worldwide, due to many

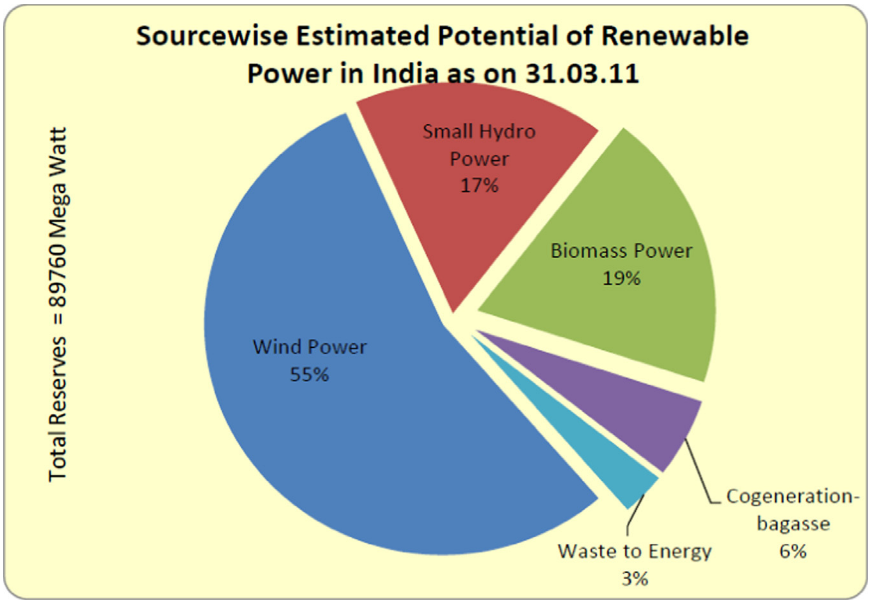

Fig. 1. Estimated power potential (source-wise) of renewable energy sources in India. *Data souce: Government of India.*

reasons as follows: First of all, the technological developments regarding biomass conversion, crop production etc. promise the application of biomass at low cost and with higher conversion efficiency [10]. For example, when low cost biomass is used as a fuel for power plants, the cost of electricity production is often competitive with the fossil fuel-based power generation. Second, the potential threat posed by climate change, due to high emission levels of greenhouse gases (particularly CO_2) has become a major stimulus for renewable energy resources [11]. When produced by sustainable means, biomass emits roughly the same amount of carbon during conversion, as is taken up during plant growth. Therefore, the use of biomass does not contribute to build-up of CO_2 in the atmosphere.

Biomass is generally classified into four main categories viz., (i) wood and woody materials, (ii) herbaceous and other annual growth materials such as straw, grasses, leaves, (iii) agricultural by-products and residues including shells, hulls, pits, and animal manure and (iv) refuse-derived fuels [12]. Among all these, agricultural biomass has huge potential for energy generation in India and the Ministry of New and Renewable Energy (MNRE), GoI has been continuously encouraging to use it for energy production. According to MNRE, about 120–150 Mt of agricultural and forestry residues are available as surplus (i.e., amount of residue left unused), which is equivalent to about 18,000 MW power potential [13]. Cereals and fibre crops contribute 58% and 23% respectively in total energy potential (Fig. 2), while the remaining 19% is from sugarcane, pulses, oilseeds and other crops [14]. It has been also found that about 92 Mt of the agricultural residues are burnt on the farms without any useful application.

1.2.2. Biomass conversion to electric power

The conversion technology for agricultural and forest biomass has been successfully implemented in various parts of the world including India, for different industrial and domestic applications. Direct heating is the most widespread application, but electricity production is gaining considerable interest among energy policy makers [15,16]. The conversion technologies for utilizing biomass can be separated into four basic categories: direct combustion processes, thermochemical processes, biochemical processes and agrochemical processes [17]. For the biomass combustion technologies with a capacity of more than 10 MW, the fluidized-bed systems are found to have relatively high efficiencies and flexibility with regard to fuel properties. Both of the combustion systems i.e. fluidized-bed systems and vibrating grates are successful in limiting thermal NO_x formation [18,19].

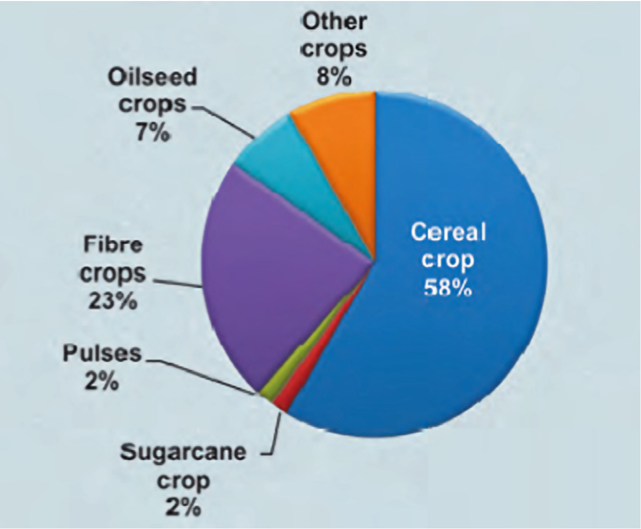

Fig. 2. The share of unutilized residues in total residues generated by different crops in India. *Data souce: Government of India.*

A large number of case studies have confirmed the feasibility and financial viability of decentralized power generation using small scale biomass gasification units [20,21]. The technical and operational feasibility of a biomass gasifier-based power generation system to meet all the rural electricity needs in an environmentally sustainable manner has also been successfully demonstrated in India [22]. The technology is on the verge of commercialization and there is need for large-scale demonstration in different parts of India along with policy, institutional and financial support for large-scale spread of environmentally sustainable biomass power systems in India and other developing countries [23]. The major problem in the biomass power generation is availability of crop residues, which varies on regional basis due to its competitive uses and agricultural practices used in a region.

1.2.3. Assessment of bio-energy potential

The assessment of the net availability of agricultural biomass for power generation is very important for successful implementation of sustainable rural energy programmes. A large no. of authors have estimated for the energy potential of biomass, using the statistical data as well as the sources of agricultural statistics and applying various statistical and analytical techniques [24–29]. Boyle [24] assessed the principle renewable energy resources that can be exploited from economic, social, environmental and political point of view, while Wereko-Brobby [25] presented an integrated framework for the teaching, research, and application of science and engineering to the sustained production, transformation, utilization and impact of biomass energy. The biomass conversion, end-use technologies and an appraisal of the costs and benefits of biomass energy was the main focus of the study. Agarwal [26] presented a comparison of the effects of crop-residue management on crop yields, including the costs and benefits from incorporation into the soil, burning residues, and harvesting for use as a fuel. Voivontas [27] assessed the biomass potential for power production using geographic information system (GIS) based decision support system (DSS), which implements the method and provides the tools to identify the geographic distribution of the economically exploited biomass potential. Sudha et al. [28] analyzed the availability of land for biomass production, the various biomass production options, biomass productivity rates, financial viability, investment required to produce biomass for energy and the barriers to biomass production in India. Wereko-Brobby [29] reported numerous assessment methods and techniques into a unitary but flexible framework, which should assist a more systematic compilation and comparison of data on biomass and its potential contribution to development.

1.3. Need of decentralized power generation in Punjab

The agricultural biomass merits a great deal of consideration in any energy development program particularly in the state like Punjab, which do not possess natural resources to meet its energy requirements. The wheat–rice rotation in the state does not allow extended delay in the disposal of agricultural residues from the farms and the farmers burn most of the crop residues. However, the smoke produced from this operation is an undesirable source of atmospheric pollution and needs to be reduced [30]. In this scenario, the preferred alternative to dispose the crop residue may be to collect the residues for some useful purpose, such as power generation [31]. The government of Punjab has already taken initiative in this regard and the Punjab Energy Development Authority (PEDA) has already commissioned six biomass based power projects with total capacity of 52.5 MW [32].

Success of such decentralized power generation programme would result multifaceted benefits to the rural people [4]. First, the conversion of non-commercial residue into valuable by-product would fest some additional income to the farmers. Second, the engagement of the rural people in collection and transportation chain would generate employment. Third, but the most significant contribution of decentralized power generation would be the development stimulated by assured supply of electricity. If the power plants are installed and operated with high thermal efficiency, the total power generation potential of rice straw can be up to 1600 MW in the Punjab state [31]. The assessment of the production of agricultural biomass is usually carried on the basis of information on the residue-to-product ratio and the total crop produced on annual basis [33]. However, the estimation of the available biomass potential of these residues as an energy source is slightly complicated, because of the problem of estimation of the fraction available for energy purpose [34]. To determine these values for implementation of biomass energy program, the resource assessment has to be carried, by considering latest statistical data and carrying literature survey for availability of agricultural residues [35]. This can be done by considerations of the availability factor i.e. the fraction of the total biomass production available for energy, which depends upon its competitive uses, and the harvesting constraints [4,36].

Since the biomass based power projects are generally of small scale and target mainly the decentralized utilization to meet local energy demand, therefore, national estimates may not be adequate for state or local bio-energy planning. Identifying this gap, the present paper investigates and discusses crop residue biomass in an agricultural based state for estimating the available electric power potential. The surplus residues from all the major crops have been considered as a sustainable fuel for generating electricity in Punjab. Based on the above discussion related with decentralized biomass conversion into electricity in the state of Punjab, following objectives have been finalized for the present study;

1. To estimate the theoretical and available biomass potential for power generation
2. To find the bio-energy and biomass power potential of crop residues
3. To study various aspects of decentralized power generation from biomass

In Section 2 the method for estimation of electric power potential of agricultural biomass is presented; in Section 3 the case study has been presented to find available biomass power potential in the state of Punjab, and Section 4 discusses various issues related with decentralized power generation in Punjab.

2. Methodology

The first step of the methodology estimates the biomass quantities generated in the form of agricultural residues on annual basis in a specific region. In subsequent steps, the surplus biomass available for energy has been evaluated taking into account the alternative uses of a particular biomass resource and agricultural practices. The bio-energy potential of various crop residues can be obtained by taking into account the energy contents of the particular crop residue, while the power potential of all these residues can be obtained by selection of appropriate technology for biomass conversion. Further, various issues such as technology options, economical and environmental impact of decentralized power generation are also discussed and reviewed. In following sections, the calculations at the each step of the evaluation procedure are outlined and the methods have been described. The information diagram for the present methodology is described in Fig. 3.

2.1. Theoretical biomass potential

It is the total annual production of the agricultural biomass in a region. Its value depends upon the annual production of the crop and the residue-to-product ratio (RPR). The theoretical biomass potential of a crop residue can be evaluated by following relation;

$$TBP = \sum_{i=1}^{n} R(i) \, X \, P(i) \tag{1}$$

The annual production i.e. $P(i)$ (tons) of ith crop is influenced by crop varieties, environmental factors and prevailing agricultural practices of the concerned region. The present study could not reflect the spatial variations of production within the region.

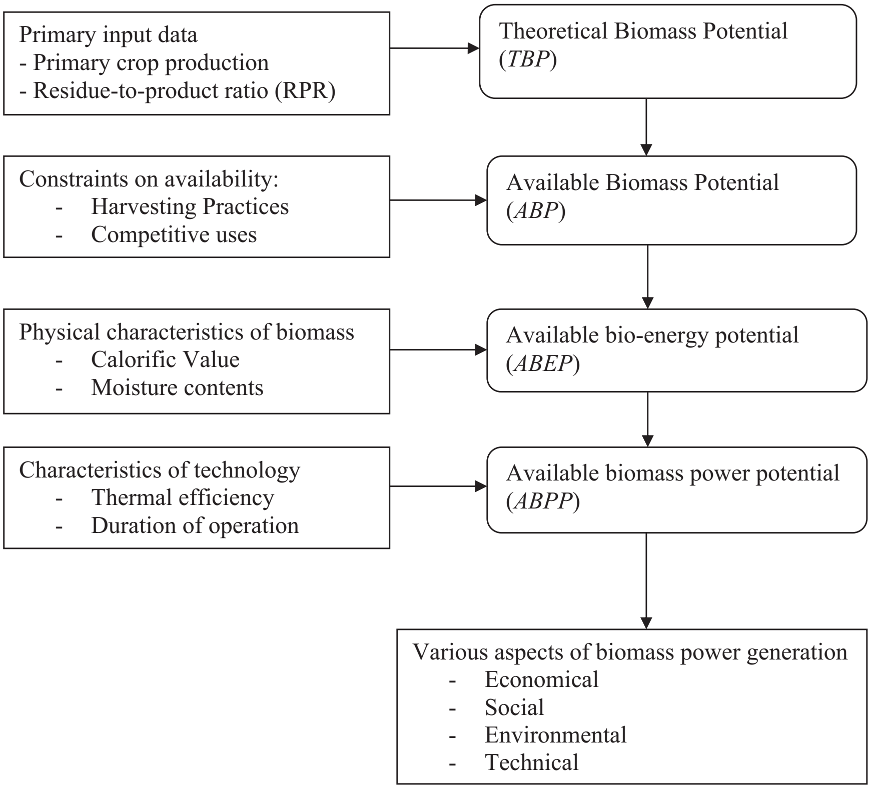
Primary input data
- Primary crop production
- Residue-to-product ratio (RPR)
Theoretical Biomass Potential (TBP)
Constraints on availability:
- Harvesting Practices
- Competitive uses
Available Biomass Potential (ABP)
Physical characteristics of biomass
- Calorific Value
- Moisture contents
Available bio-energy potential (ABEP)
Characteristics of technology
- Thermal efficiency
- Duration of operation
Available biomass power potential (ABPP)
Various aspects of biomass power generation
- Economical
- Social
- Environmental
- Technical

Fig. 3. Flow diagram depicting information required for assessing energy potential of agricultural residue.

Table 1
Data collected for estimation of power potential of crop residue in Punjab.

Group	Crop	Production[a] (Mt)	Residue type	RPR	CV[b] (MJ/t)
Cereal	Rice	10.888	Husk	0.2	15540
			Straw	1.5	15540
	Wheat	16.291	Pods	0.3	17150
			Stalks	1.5	17390
	Maize	0.495	Cobs	0.3	17390
			Stalks	2	16670
	Barley	0.045	Straw	1.3	18160
Others	Cotton	1.935	Boll Shell	1.1	18300
			Husk	1.1	16700
			Stalks[c]	3.8	18300
Sugarcane	Sugarcane	0.440	Bagasse	0.33	20000
			Top & leaves	0.05	20000
Sources		Ref.[35]		Ref.[38–40]	Ref.[38]

[a] All values for production of crops are on five year average basis.
[b] Calorific value for the residue for specific moisture contents.
[c] Tons per hectare (area under cotton 5.12 million hectares).

Moreover, the spatially varying information concerning the variety and growing practices are also not considered in this study. However, from the preliminary investigation it is found that traditional varieties of crops with a uniform average production are predominantly grown by the farmers. This is reflected in the statistical record that the yield of the major crops (rice and wheat) is almost constant over the last few years throughout the state. However, five year average production of the crops (from 2008–2009 to 2012–2013) as reported by economic advisor of state government in the *statistical abstract of Punjab-2013* is used for investigations in order to minimize yearly fluctuation in crop statistics [35].

The residue-to-product ratio i.e. $R(i)$ indicates the amount of residue available for each ton of ith crop produce. Thus, an RPR of 2 would indicate that 2 t of crop residues are produced for every 1 t of crop production. Residue production yields depend mainly on agricultural practices and it varies from region to region [27]. For example, in case rice is cut at about 2 in. above ground, the RPR of rice straw equals 1.75, whereas, it falls to 0.452 if only the top portion of the rice stem is cut [37]. The value of $R(i)$ is obtained from laboratory investigations of commonly grown varieties in the concerned regions and is readily available in literature [38]. A similar RPR value for rice and wheat straw was also reported by earlier investigation [39] and given in Table 1. Therefore, combining the relevant information and using Eq. (1), the data regarding the gross biomass potential from major crops within the defined geographical boundaries can be evaluated.

2.2. Available biomass potential

The theoretical biomass potential is subject to restrictions introduced by alternative uses of the agricultural residues, as well as the agricultural practices used in a particular region [25]. The potential uses of the agricultural wastes are specific to the crop and residue, and when they are taken into account the amount of residues available for energy production can be evaluated. More are the competitive uses of biomass, lesser is the availability. The farming and harvesting practices as well as efficiency of collection machinery varies considerably from region to region. With manual methods of harvesting, there are wide variations of height of cut and accordingly its availability. Therefore, harvesting and threshing practices have remarkable influences on availability of surplus crop residue. To incorporate such uncertainties, available biomass potential is estimated using an availability factor as given below;

$$ABP = \sum_{i=1}^{n} R(i)\ X\ P(i)\ X\ A(i) \qquad (2)$$

A large number of investigations are carried to find the availability factor $A(i)$ for a particular crop residue, using geographical information system and the statistical data in India, especially in Punjab [37–44]. According to Singh et al. [40], residue straw (wheat and rice) is the major surplus crop residue available in the Punjab state with a contribution of 74.81% to the total crop residue production (13.73 million tons). It can be used to fulfill 15% of the total energy requirements in the state. Gadde et al. [41] reported a value of 48% for availability factor for rice straw for the states of Punjab and Haryana of India. In India, 23% of rice straw produced is surplus, which is either left in the field as uncollected or subjected to open-field burning. Singh et al. [42] found that 83.5% of the rice straw is surplus in the state of Punjab in India. For rice husk and other crop residues, a similar availability factor of 75% was also reported by Purohit [43]. It has also been revealed that the wheat straw is relatively sturdy and it is commonly used as animal feed in most area of the state, while the farmers do not prefer rice straw as dry fodder [44,45].

2.3. Available bio-energy potential

For a specific biomass resource, available bio-energy potential represents the energy contents that can be technically and economically harvested and used for energy purpose. Its value is bounded by the collection mechanism and characteristics of the biomass resources and the characteristics of the selected production technology. This can be obtained by using following equation;

$$ABEP = \sum_{i=1}^{n} R(i)\ X\ P(i)\ A(i)\ X\ C(i) \tag{3}$$

where $ABEP$ is the crop residue bio-energy, MJ and $C(i)$ is the lower calorific value of the ith crop, MJ t^{-1}. The spatial variation of $C(i)$ is not accounted in the present investigation. The average calorific value of crop residues as reported in literature is used in the present analysis [42]. The main residue available from cereals cultivation is straw, which can be considered as a major source of energy. In addition to this the other residues as presented in Table 1 also have significant potential to be used for the analysis. Available data on calorific values with water content within specific limit is used in the evaluation of the biomass energy contents [38,44].

2.4. Available biomass power potential

The technology selection to exploit the biomass from various crops depends on the particular energy needs and the efficiency of the energy production process. Crop residue fuel characteristics including the moisture contents would influence the decision of appropriate conversion route. In general, thermal conversion of biomass requires low moisture content (less 50%), while bio-conversion can utilize high moisture feedstock [42]. The combustion is a mature technology among thermo-chemical conversion technologies, specifically suitable for loose biomass [46]. The combustion process converts chemical energy stored in biomass into heat, mechanical power and electricity using various equipments, e.g. furnaces, boilers, steam turbines and generators.

With this technology, it is possible to burn any type of biomass up to a moisture content of 50% [4]. The size of combustion based biomass power plant ranges from a few kW up to hundreds MW with net conversion efficiency between 20% and 40% [18,47,48]. Therefore, incorporating net conversion efficiency for biomass combustion and duration of operation, available biomass power potential is determined as given in the following expression:

$$ABPP = \frac{\left[\left\{\sum_{i=1}^{n} R(i)\ X\ P(i)\ X\ A(i)\ X\ C(i)\right\}\ X\ K\right]}{T} \tag{4}$$

where $ABEP$ is the available biomass power potential for a specific region in kW, K is the overall energy conversion efficiency and T is the annual operating duration in seconds. Therefore, by selecting appropriate conversion technology with a value for conversion efficiency and average operating hours, the available biomass power potential can be evaluated.

Further, it may be noted that the size of the power plant is also a matter of concern as the larger plants may cost less to build per unit of output capacity. But, it will involve more transportation charges to collect fuel from the fields distributed over a larger distance. The necessary information required for calculating the optimum size of power plant is the available biomass potential, the technical characteristics of the plant and costs related with logistics of biomass collection [49].

The size or capacity of a power plant alone does not necessarily mean that it produces large or small amount of electricity. The amount of electricity that a power plant actually produces and what it could potentially produce if the plant were run at full capacity over an entire year offers a ratio that is known as the capacity factor. Numerous aspects within and outside the biomass power sector influence the capacity factor of biomass power plants: ability to ramp power production, grid demand, plant maintenance, feedstock availability etc. Therefore, the actual exploitable power generation potential can be obtained by taking into consideration the capacity factor for biomass based power plants [27,31].

3. Case study: Available biomass power potential in Punjab

3.1. Background of the state

The state of Punjab is situated in Northern India, and it has total land area of 5.036 million hectare. The total area under cultivation was 4.159 million hectare during year 2012–2013, representing about 83% of the total land area of the state [35]. Although the land in the state is intensively cropped with wheat and paddy, but a wide diversity of other crops are also grown. Agriculture is the major sector influencing the economy of the state. Therefore, it is expected that the residues emanating from farming sector will be significantly large for generating electricity.

The total installed plant capacity for electric power generation has been measured as 7 GW, while total demand for electric power has been found to be 11 GW for year 2012–2013. Apart from the hydro and steam power generation, the state government has planned to explore renewable energy resources, to overcome the deficiency of electric power. Although, the actual power generating capacity of these resources may be quite high, but the state is currently planning 500 MW of power generation from non-conventional resources in near future. In this scenario, the present study would be useful for the society, policy makers, planners and engineers concerned with mechanization, to get optimum returns out of it. The state has been selected for the aforementioned reasons, as a case study, to highlight the applications of the developed methodology.

3.2. Data input sources

The statistical data regarding the production of cultivated crops is taken from the state's agricultural department, while data on the availability of various crops and the residue-to-product ratio has been taken from recent investigations. The following data for Punjab state has been used in the present case study:

- Statistical data for crop production and types of cultivation
- Data on characteristics of the residues produced from major crops

– Current uses of the residues and harvesting practices
– Technical characteristics of the biomass conversion facility

Table 1 shows the summary of the data used to apply the methodology discussed in Section 2, for estimating power generation potential in Punjab's context. The methods for calculating the data regarding crop production, RPR and calorific value (CV) for various crop residues is discussed in the references listed in Table 1.

3.3. Results and analysis

3.3.1. Theoretical biomass potential

The crops considered in this study include rice, wheat, maize, cotton and sugarcane as these are the major crops grown on rotation basis in the state. The annual estimates of the crop production are taken from the *statistical abstract of the Punjab* on five year average basis, from 2008–2009 to 2012–2013, while the value for residue-to-product ratio for each crop are derived from latest literature [38,39]. Table 1 and Eq. (2) were used to obtain the theoretical biomass potential i.e. the total amount of biomass generated in the state of Punjab. Crop wise detail of the residue production is shown in Table 2.

It is estimated that the average residue production is about 55.396 Mt in past five years. The three major residue producing crops are wheat, rice and cotton that contributed in the total residue production as 55.93%, 33.43% and 11.19%, respectively. The results are in line with those obtained in other investigations [50–52] carried at Punjab Agricultural University (PAU) Ludhiana, in which the total biomass potential from agricultural crops was estimated to be 55.54 Mt, 46.16 Mt and 54.54 Mt, respectively. In these studies, the spatial distribution of biomass potential from crop residues and agro industrial waste was studied at block level for power generations using geographical information system (GIS). According to another study conducted by Chauhan [53], around 40.142 Mt of the total crop residue is generated from various major and minor crops in the Punjab state. Therefore, the present results along with the earlier investigations confirm that a significant quantity of the residue is produced on annual basis in the state. This theoretical biomass potential represents the amount of the crop residue generated at the farms and its utilization as an energy resource will depend upon the availability of these residues for energy purpose, as they may be used for some applications by the farmers [4,39]. To present a realistic figure regarding the potential of crop residues, an availability factor has been introduced in the succeeding sections.

Table 2
Estimating theoretical biomass potential in Punjab (crop-wise).

Group	Crop	Residue type	Residue production (Mt)	%Age
Cereal	Rice	Husk	2.177	33.43
		Straw	16.332	
	Wheat	Pods	4.887	52.93
		Stalks	24.436	
	Maize	Cobs	0.148	2.05
		Stalks	0.990	
	Barley	Straw	0.058	0.1
Others	Cotton	Boll shell	2.128	11.19
		Husk	2.128	
		Stalks	1.945	
Sugarcane	Sugarcane	Bagasse	0.145	0.3
		Top & leaves	0.022	

Note: All values for production of crops are on five year average basis.

3.3.2. Available biomass potential

Based on the total production of the crop residues and consideration of availability factor for a particular crop residue, the availability of crop residues for energy purpose is estimated. The results presented in Table 3 show that the total surplus quantity of the residues for bio-energy production is about 22.315 Mt. The residue emanating from the cereal crops (rice, wheat, maize and barley) is the major contributor (74.69%) towards the surplus residues, followed by cotton (25%) and sugarcane (0.31%). Although, wheat is the major residue producing agricultural crop in the state, but the rice crop produces the highest quantity of surplus residues, as they are not used for any gainful application.

Based on the present observations, the average density of the surplus biomass was found to be 443t km^{-2}. For the estimation bio-energy potential, it is assumed that the biomass residue is uniformly spread over the entire area. This assumption does not influence the total bio-energy potential in the state, because the lower residue density in certain part of the state will be recovered by the higher distribution of residue in other parts.

The availability factor for different groups of crop residue is taken from the latest investigations [38,39], which presents state-wise availability of surplus crop residues. The total surplus biomass in other studies conducted at PAU was observed to be between 28 Mt and 30 Mt [50–52]. The surplus biomass for energy generation was also estimated at block level using the residue product ratio taking into consideration the existing status on availability and in house utilization of biomass.

3.3.3. Available bio-energy potential

Based on the conversion efficiency for a particular technology, thermal values of each crop residue, the available biomass potential and the bio-energy potential of crop residues has been evaluated (Table 4).

The results presented in Table 3 indicate that the total bio-energy potential from residues in Punjab can be equivalent to 0.35 EJ. This bio-energy potential represents about 8.4% of annual bio-energy potential of all the crop residues in India (4.15 EJ), and

Table 3
Estimating available biomass potential (crop group-wise).

Group	Availability[a](%)	Residue production (Mt)	Surplus residue[b] (Mt)	%Age
Cereal	34	49.02	16.669	74.67
Others	90	6.201	5.581	25.01
Sugarcane	40	0.167	0.066	0.2
Total		**55.396**	**22.315**	
Sources	Ref.[36]			

[a] Surplus fraction of residue availability (% of group wise surplus residue).
[b] Group wise availability.

Table 4
Estimating the available bio-energy potential.

Group	Surplus residue (Mt)	CV[a] (MJ/t)	*ABEP*[b](MJ)
Cereal	16.669	16000	2.6×10^{11}
Others	5.80	17000	9.8×10^{10}
Sugarcane	0.0668	20000	1.3×10^{9}
Total potential			$\mathbf{3.5\times10^{11}}$

[a] Calorific value of the crop residues on average basis.
[b] Group-wise bio-energy potential calculations.

it is also equivalent to 1.4% of India's total primary energy consumption [38]. It has been also found that there is significant variation in per capita bio-energy availability among the states of India, which range from the lowest in West Bengal (679 MJ) to highest in Punjab (16,860 MJ). Punjab is further followed by Haryana (11,559 MJ per capita) and Gujarat (6660 MJ per capita) in bio-energy potential. Therefore, this information is expected to be useful for decentralized crop residue based energy planning in the Punjab state of India, which in turn would positively influence the overall renewable energy growth in India.

3.3.4. *Available biomass power potential*

This represents the total energy contents of the residues that can be exploited by using thermal values of each residue. To calculate this potential the efficiency for direct combustion technology has been considered to be 20% while operating 18 h (6570 h per year) on daily basis.

Table 5 shows that the available biomass power potential of the crop residues may reach 3099 MW at a thermal conversion efficiency of 20%. If the efficiency of combustion technology increases to 25%, the available biomass power generation potential increases to 3917 MW under same operating conditions. These are based on the average calorific value for different crop groups and the spatial variation in the calorific value is not considered.

The results reveal that as the thermal efficiency drops, the energy potential of residue also decreases along with increase in the unit production cost and the investment required.

3.3.5. *Exploitable biomass power potential*

The relationship between the generation potential and the fuel requirements as the function of conversion plant efficiency has been shown in Fig. 4. The 3760 MW potential of electric power has been indicated in figure as 2937 MW at a capacity factor of 75% [31]. If the conversion efficiency declines to 20%, the generating potential will also decline to 2375 MW. Hence, the importance of thermal efficiency in the design of power plants is clearly evident and needs to be taken into consideration during installations of power units.

The results obtained are very close to those obtained by Kaur et al. [52], who found that there exists a total potential of 2000 MW of power generation from the surplus biomass in Punjab. In other investigations, Chauhan [53] found that around 1.510 GW and 1.464 GW of electric power can be generated through basic surplus and net surplus biomass in the state respectively, while Singh et al. [42] indicated an energy potential of 900 MW from unused agricultural biomass.

A report prepared for US Department of Energy discusses a detailed technical and economic evaluation of woody biomass conversion to electric power and also as cogeneration with steam [54]. It reported 21% thermal efficiency in electric power generation with 80% capacity factor, 7008 h per year of operation and a plant life of 20 years. On the scale of economy, the investment on plant facility goes down from 1090 US Dollar/kW for 25 MW to 940 US Dollar/kW for 150 MW. As plant size increases from 25 MW to 150 MW, the revenue requirements decrease by 10–20%. Therefore, plant size is significant criteria in optimization of the electricity production and it is very much clear and verified in the present study.

Table 5
Estimating available biomass power potential.

Group	*ABPP*[b] (MW)	*ABPP*[c] (MW)
Cereal	2255	2819
Others	833	1042
Sugarcane	11	56
Total power potential		
Available	**3099**	**3917**
Exploitable [a]	**2375**	**2937**

[a] On considering capacity factor of 75% for the power generation.

[b] For thermal conversion efficiency of 20% and time of operation is 6570 h per year.

[c] For thermal conversion efficiency of 25% and time of operation is 6570 h per year.

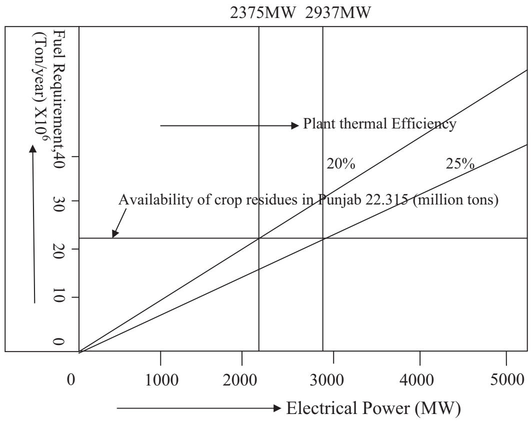

Fig. 4. Power generation potential at different thermal efficiencies.

It has been also revealed that the power production cost from a biomass-fired power plant depends upon various parameters such as capital cost required for biomass management (purchase, storage, collection and transportation), and operation and maintenance of the plant. Each plant should be designed with optimum capacity and collection area, so as to provide electricity at competitive price [31,49,55].

4. Various issues in decentralized power generation

The study reveals that the biomass based decentralized power generation has been found to be essential for achieving energy security and the sustainable development in near future. As most part of the state is cultivated by various major and minor crops, therefore it is expected that the crop residues are uniformly spread over the entire area of the state [35]. But, the biomass power potential of these crop residues should be obtained taking into account a number of conservation issues: resources (total amount, availability), economy (electricity cost, transportation costs), environment, and technology [56]. This section discusses various issues related with biomass based decentralized power generation in Punjab.

4.1. *Economical aspects*

4.1.1. *Electricity production cost*

Punjab has been meeting its electrical power requirements primarily through conventional thermal and hydro power generation. The availability of power from hydro power plant has tendency to fluctuate depending upon the availability of water and the government has to explore the possibilities of setting up thermal power plants. But, the thermal power generation has to depend upon coal, which has to be transported from eastern part of India. It involves large distances and the generation cost from coal continues to escalate. Moreover, the transmission/distribution losses in hydro/thermal power generation are around 35%, and when these losses are taken into consideration, the generation cost increases to around Rs. 15/kW h [57].

As the biomass power will be produced and consumed locally and the plants will be working on decentralized basis, therefore the proximity of the biomass power plants to the villages reduces the transmission and distribution losses to less than 3%, as the biomass generated power is distributed over a short distance and the generation cost varies from Rs. 3 to 4/kW h depending upon the plant load factor [58]. Under these circumstances, bio-electricity can be considered as the cheapest to generate and deliver, even without any administered costs/prices.

4.1.2. *Employment generation*

According to MNRE, biomass power generating unit can produce a significant economic benefit to the area surrounding the plant [58]. It is expected that a 10 MW biomass power project can create approximate employment for 100 workers during the 18-month construction phase, 25 full-time workers employed in the operation of the facility, and 35 persons in the collection, processing, and transportation of biomass material.

In addition, there is other income to the rural economy in growing and harvesting of biomass. There is no other capital investment that can generate this much income per annum, perpetually, to the rural economy. The proximity of the plant to villages also ensures availability of manpower for operation and maintenance of the biomass power plants [57]. Therefore, the bioelectricity generation will involve creating a lot of opportunities among the local people for the biomass management, operation of plant and maintenance of equipments in the plant.

4.1.3. *Investment required*

The capital cost of investment required for installation of biomass plant varies from Rs. 4.5 to 5.0 crore/MW depending upon technical, financial and operating parameters [58]. Therefore, the total investment required for setting up biomass conversion facilities to generate 2.9 GW of electric power lies in the vicinity of Rs. 2.0×10^{11}. This investment is much lower than the cost of recently completed thermal power plant in Bathinda district of Punjab, which was estimated at 1.1×10^{12} with electric supply of 2 GW. The relative advantages and disadvantages of the two types of the system are still debatable, but that is not included in the present study [31].

Although, mobilizing such an investment may be difficult in a short time frame, but the investment in biomass energy can bring the state at par with the developed nations. Punjab has only 2% of India's population with 4% contribution in electrical capacity. It is unlikely that Punjab can develop its own resources in isolation, and perhaps it is not desirable. The efforts have to be made to enhance the applications of surplus biomass in generating power, by mobilizing sufficient funds into this sector.

4.2. *Social aspects*

4.2.1. *Energy security for rural areas*

Clearly, an energy deficit of the order of 4 GW can be alleviated, if the energy potential of agricultural biomass of the order of 2.9 GW, as indicated in the present study is realized along with installation of plants from conventional resources. In order to achieve this, a number of medium scaled, locally sited, interconnected power plants could be utilized in the conversion of rice straw or other biomass materials [31]. Balachandra [59] advocated the utilization of biomass resources potential to produce adequate amount of modern energy for decentralized utilization in rural areas of India. Village level decentralized biomass power generation of kilowatt scale has also been commissioned in various parts of the country. In a recent study, Dasappa et al. [60] reported deployment of six biomass gasifier based power plant projects with total installed capacity of 0.88 MW in Tumkur district of Karnataka.

The previous investigations also indicate that the biomass power plant with capacity of 7.5 MW to 10 MW has been found to be economically viable and beyond this capacity the logistics of managing the raw material would be difficult [58]. The study regarding transmission and distribution should be carried at block level. Gasification bio-energy units can be set up in a modular design so that if one engine/reactor is shut down for maintenance, the other reactors/engines can continue generation in the modular design, thereby continuing power supply to the villages.

4.2.2. *Management of power plants*

Ideally, the capacity for the entire load can be established in three or four phases, over a period of 12–15 years, to enable development of management skills as well as capacity building for operation and maintenance of the plants [57]. In addition, it will enable the accurate determination of the availability and the potential for growing biomass for maintaining sustainability. It also enables setting up improvised systems, which come up with technology up gradation, over a period of time. Therefore, biomass growers, suppliers and the bioelectricity users are considered as the stake holders, in this model of rural electricity security. As stake holders, they are best suited to operate, maintain, manage and administer the power plants, fix prices for the biomass, labour costs, power productions targets as well as tariffs from the bioelectricity users. Social engineering requires to be done in the jurisdictional communities, to build up their capacity to administer and manage the power plants and also to trade in surplus renewable energy. According to Balachandra [59], India has local expertise in developing and deploying biomass gasifier technologies for power generation to ensure proper operation of the plants.

4.3. *Environmental aspects*

4.3.1. *Sources of pollution*

Due to sudden increase in the energy requirements in the state, the state government has planned to install thermal power plants in different areas of the state (Rajpur, Bathinda). The coal is the fuel used in these plants and it is a major source of environment pollution. These plants cause respiratory and related ailments to human beings, while causing threat to the existence of animals and plants [61]. In addition to this, the burning of crop residues in the fields is already is major source of green house gas emissions and its impact [62,63]. In another study, the burning of agricultural residue (stalks and stubble) in the fields during wheat and rice harvesting periods, in the Indo-Gangetic plains, has been found as an important source of atmospheric pollution in the region [30].

It has been confirmed in the earlier studies that the emissions from the burning of fossil fuels and biomass have led to the creation of atmospheric brown clouds of black carbon and aerosols in various parts of the world, which should be targeted to mitigate climate impacts and improve air quality [64]. Emissions of black carbon are the second most contribution to current global warming, after carbon dioxide emissions [65]. The authors' claim that in the Himalayan region heating from black carbon at higher elevations has as large an effect on the melting of snow glaciers as heating due to greenhouse gases. Furthermore, when black carbon is deposited over snow and sea ice, it darkens the snow thereby significantly enhancing solar absorption by snow and ice leading to a retreat of the Arctic sea ice. It is also well established that large concentration of aerosols leads to the creation of fog that reduces visibility causing multiple accidents and delays in road, railway and air transport. Consequently, regional climate and the health of the population are adversely affected.

4.3.2. Biomass as a clean energy resource

In this scenario, biomass energy presents the cleanest technology available to the mankind, to mitigate global warming and climate change, while creating rural employment in biomass management and power generation. The biomass power can be collectively pumped into the state electricity grid. It will reduce the direct burning of the residues on the fields and simultaneously the generation of thermal energy from the polluting coal is reduced. Therefore, the biomass energy can provide the road map for any action plan on climate change and energy security, but the issues related to installation of the power plant and distribution of electricity to the consumer should be resolved, carefully [57].

4.4. Technical aspects

4.4.1. Logistics of collection

In order to utilize the biomass resources available in the state, the crop residue generated in the field has to be made available to the utility point. The supply chain for the biomass based plants involves collection, storage and transportation of residue from field to user site. Therefore, the logistics of the fuel supply have a large impact on the economy of a biomass utilization facility, especially for low density biomass fuels like rice straw [66], which is the major surplus residue in the state. Studies have shown that the costs for all operations may vary from region to region depending upon baling techniques used for the collection purpose [67].

For implementation of bio-energy program, harvesting and transportation costs are the major components influencing the energy potential. Prevailing practices of harvesting vis-à-vis scope for introducing mechanical methods of harvesting also influence the viability of crop residue based power plant. Gupta et al. [68] attributed the open field burning of crop residues to combine harvesters that leave a large amount of loose residue on the field, while Erenstein et al. [69] assert that a major constraint in a rice-wheat cropping system is the available short time between harvesting and sowing of the next crop. Given this short time and non availability of biomass management, farmers find it difficult to utilize the residue and hence opt for burning.

Moreover, the biomass transportation cost is a function of the quantity of available biomass in a region and the transportation distance. GIS is an important tool, which can be used for investigation of the location of biomass conversion facility for minimum cost of electricity taking into account all economic parameters [27]. It will also ensure the availability of adequate biomass near the power plant.

For crop residue collection, it is important to properly interface the collection system with the grower's own operations as the farmers do not tolerate any interference with harvesting operations and do not change their operations to facilitate straw harvesting without economical motivations [70,71]. New regulations should provide farmers with an economic incentive to cooperate with collection of crop residues.

4.4.2. Densification of biomass

The crop residue generated in the field has to be made available to the utility points. The supply chain involves collection, storage and transportation of residue from field to user site. All these processes influence the resulting feedstock cost [38]. The bulky nature or low energy density of agricultural residues possesses problems in handling, storage, transportation and conversion processes. Densification increases energy density of biomass and also makes transportation and storage economical [72]. Biomass densification can be done via two processes (i) mechanical (e.g. bales, pellets, cubes, briquettes) and (ii) pyrolysis (e.g. torrefaction, slow pyrolysis, fast pyrolysis).

Appropriateness of the processes is to be judged based on the situation specific consideration. The results of the recent investigations indicate that the abundant agro-residue resources can provide the economical and sustainable raw material for densified solid biofuels in developing world [73]. With continued improvement and cost reduction of briquetting technology, along with the support of national energy policy on biomass energy, the densified solid biofuels from agro-residues can be gainfully used for energy production. But a careful identification of historical, industrial, geographical, and energy-related similarities must taken into account to find the feasibility for crop-residue densification plants in different regions [74].

4.4.3. Development of combustion systems

Thermal conversion technologies can also use high moisture content feedstocks, but the overall energy balance for the conversion process is adversely impacted. Moisture in biomass fuel reduces the heating value, thus if too much moisture is present, the fuel will not react spontaneously [75]. Moisture content of herbaceous and agricultural residues may vary from about 9 to 35% depending on the plant species [76]. Therefore, for the design of efficient large-scale biomass combustion systems a lot of parameters have to be taken into account. These parameters are the mean value and the variability of moisture, the volatile matter content, ash content, ash composition, agglomeration characteristics and the energy content of the fuel. Further, the furnace design will depend on the emission limits that have to be kept minimum. Combustors for agricultural waste fuels are predominantly grate-fired systems, suspension burners or fluidized bed systems [77].

Grate-firing systems have some specific advantages which include being able to handle fuels with high moisture contents up to 65 wt% water, low investment costs and also low operating costs [78]. Further advantages are the good burnout of fly ash particles and the low dust load in the flue gas. Fluidized bed combustors are used worldwide to combust both coal and biomass. The inherent advantages of fluidized beds make them an attractive option for the combustion of agricultural residues. The NO_x emission control by air staging in fluidized bed reactors has been thoroughly investigated and is working well. The combustion intensity in fluidized bed combustors is higher than that in grate-fired systems. To combust agricultural residues in suspension burners, it is required that they are dry (e.g. less than 15 wt% moisture contents) and finely divided (e.g. particle size, 2 mm).

4.5. Future scope and challenges

It has been revealed that the commercial exploitation of biomass energy suffers from a number of logistics and technological challenges. The supply chain management, pretreatment and conversion of biomass to gas, and cleaning and utilization of gas for power generation are the critical factors to be resolved carefully [79]. The recent study shows that the gasification of biomass and gas cleaning are the most challenging part for utilization of biomass [80]. For electricity generation, either using engine or gas turbine requires a stringent specification of gas composition and tar concentration in the product gas. Different types of updraft and downdraft gasifiers have been developed for gasification and a number of physical and catalytic tar separation methods have been investigated. However, the most efficient and popular one is yet to be developed for commercial purpose. According to the recent report, an advanced gasification method with efficient tar cleaning can significantly reduce the biomass consumption, and thus the logistics and biomass pretreatment problems can be ultimately reduced. In spite of all these problems, the focus is on identifying and maintaining sustainable and environmentally friendly energy resources, by means of the clean development mechanism (CDM) [81]. It will emphasize the strategic importance of biomass energy, especially in areas where it is economically attractive because of the ready availability of resources. Considering the irregular power supplies, power cuts and availability of resources in the study area, the crop residue based power generation could be an attractive and economically viable option to meet rural energy supply.

5. Conclusion

The use of agricultural residues as a substitute for conventional fuels has been found to be essential for preservation of natural resources and the overall protection of the environment. In order to develop any policy on the use of residues, it is also important to know the electric power potential of these residues. In this paper, a methodology has been presented, for estimating the availability of agricultural residues for distributed power generation. The methodology has been tested in the state of Punjab, where the execution of various steps has been illustrated. The total potential of agricultural biomass in Punjab was 55.396 million tons (Mt) and it was found that out of total biomass potential about 40.17% of biomass (22.315 Mt) was surplus with average biomass intensity 443 t km^{-2}. At a capacity factor of 75% the available biomass power potential is represented as 2000–3000 MW depending upon the thermal efficiency. Although, it may be difficult to realize this in a short time frame, but it is important to recognize the technical and economical needs of biomass power plants from engineering point of view and for sustainable development of the state. The information generated in this study is expected to be useful for setting up decentralized power plants in the Punjab, which in turn would positively influence the overall growth of renewable energy in India. Thus, it is seen that there are several important issues concerning the bio-energy utilization of crop residues *viz*., (i) availability of crop residues, (ii) practices of collection, handling and storage, (iii) appropriate technology of conversion suiting fuel characteristics, (iv) economy of fuel substitution which are expected to vary amongst the states of India. The potential estimates of the present investigation are required to be considered keeping in mind of such varying dynamics.

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